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Storage life of silicone rubber sealing ring used in solid rocket motor

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Abstract It is urgent to carry out detailed research on storage performance of rubber sealing ring to get the criterion for its storage life. This paper acquires material ageing regularity by theoretical analysis and experimental confirmation. On this condition, failure mode and failure criterion of typical sealing structure is studied, and the failure mechanism is found. Thus by analyzing the stress distribution, the relationship between ageing state and sealing condition is established. Rationalization proposal is put forward and storage life of sealing ring is evaluated. The research mentioned-above has special reference to the design of sealing structures and can provide reference for prolonging their service life.

1. Introduction

Silicon rubber sealing ring is widely used to encapsulate different components of the solid rocket motor (SRM). Its reliability plays an important role in the safety and service life of the solid rocket motor. Developed countries have devoted to extend the solid rocket motor service life and have gotten significant achievements. It is reported that the service life of the solid rocket motor in America and Russia has been reached as long as 20 years, which cannot be separated from the theoretical and experimental study on sealing materials and structures. Clinton and Turner[1] conducts researches on stress decay of the sealing ring and points out that its storage life can reach 6 months when the compression ratio is more than 15%. Bower[2] comes to a conclusion that the compression ratio of the O-ring is inversely proportional to the stress decay. Ralph[3] carries out experimental research on storage life of the O-ring from the permanent deformation in compression perspective. The related literature[4] summarizes molecular theory of elasticity of the rubber materials used in sealing rings, and Rivlin[5] puts forward their stress–strain relationship. In the 1980s, the stress characteristics of the sealing ring have been widely researched. Salita[6] compiles simplified finite element programs to calculate the stress and strain. Gadia[7] performs his researches on incompressibility of the materials used in sealing rings.

Over the past 40 years, great changes have taken place in storage life of the solid rocket motor in our country. Test method for accelerated aging and properties of materials for

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sealing rings has been researched, but their storage performance data is still deficient. With the rapid development of the finite element technique, a lot of stress–strain analyses have been carried out. Hu et al.[8] inquires into the stress distribution of the sealing, and Ren et al.[9–11] calculates the deformation and stress state of the O-ring with model Neo–Hookean and model Mooney–Rivlin. Mu and Xing[12] conducts researches on necessary and sufficient conditions for sealing and the distribution law of contact stress. The study on aging property of sealing materials also strengthens gradually. Rong[13] introduces the accelerated aging test method of the rubber materials and Xiao and Wei[14] evaluates the storage of the vulcanized rubber.

Although more and more attention has been paid to sealing structures, most of the study still focuses on the theoretical level. The theoretical analysis concerns about the various stress state of the sealing structure except the correlation between the stress state and the compression storage of the sealing ring, which directly results in deficiency in the storage life analysis of the sealing ring.

This paper devotes to seek a breakthrough in the correlation between the stress state and the aging state. In the course of this study, stress distribution and the compression aging law of the sealing structure have been researched in full detail. The permanent compression deformation is taken as the main aging characteristics to establish contact between stress distribution and aging time, thus to obtain the stress state in various storage periods. The evaluation criterion related with the compression ratio of the sealing ring is also proposed, and a reasonable evaluation for storage life of the sealing ring is given which is verified by experiments.

2. Aging property experiment

Thermal acceleration experiment is carried out to test aging property of rubber sealing ring. The compression ratio of standard cylindrical specimen in permanent compression deformation is 25%, and test temperature varies from 100 °C to 140 °C according to different material characteristics. The permanent compression set value in different aging states is achieved by different tests at different aging temperatures and different aging time, and compression aging property depending on the aging time at normal temperature or aging temperature is obtained by data fitting. Compression aging property in different aging states is shown in Table 1. The conclusion that compression permanent deformation increases with the storage time and aging temperature is drawn from the analysis of the experimental data.

Table 1 Compression aging property of silicon rubber.

Aging time (day)	Compression permanent deformation ratio				
	100 °C	110 °C	120 °C	130 °C	140 °C
1	0.92	0.91	0.89	0.86	0.86
2	0.90	0.87	0.87	0.82	0.79
4	0.87	0.82	0.80	0.73	0.69
10	0.80	0.74	0.69	0.62	0.59
20	0.73	0.68	0.64	0.56	0.51
30	0.69	0.65	0.60	0.50	0.45
40	0.70	0.66	0.61	0.50	0.42
50	0.69	0.57	0.64	0.44	0.38
70	0.63	0.56	0.48	0.38	0.28
82	0.62	0.59	0.49	0.35	0.29
90	0.61	0.55	0.46	0.34	0.24

According to the aging property of rubber material and related Refs.[10,15], this article assumes that the compression aging property of silicon rubber is consistent to power index model as shown below:

$$f(P) = B\exp(-Kt^{\alpha}) \tag{1}$$

$$K = Z\exp(-E/RT) \tag{2}$$

where $f(P)$represents compression aging property in different time nodes, P is compression permanent deformation ratio, B and α are model parameters. Both aging reaction rate K and thermodynamic temperature are in accordance with Arrhenius formula.[16,17] In the Arrhenius formula, Z is aging rate parameter, while E is material apparent activation energy, R represents Molar gas constant, and T is aging temperature.

According to the test data lists above, model parameters and aging reaction rate at different temperatures can be fitted, and model parameters at normal temperature can be derived. Parameter model α is processed by successive approximation. Taking total departure I (see Eq. (3)) as the criterion, α is solved to be 0.4, and aging reaction rate K at room temperature is 0.0123. Taking value of model parameter B for 1, aging property model $f(P)$ at room temperature is obtained as shown in Eq. (4). In the successive approximation, f_{ij} is the function value under a certain parameter, and $\hat{f}_{ij}$ is its optimal value. Aging property curve of silicon rubber at room temperature is shown in Fig. 1.

$$I = \sum_{i}^{p}\sum_{j}^{n}(f_{ij} - \hat{f}_{ij})^2 \tag{3}$$

$$f(P) = \exp(-0.0123t^{0.4}) \tag{4}$$

Aging property experiments of sealing ring are also carried out to grasp the difference between sealing ring and standard cylindrical specimen, and experiments with and without lateral constraint are also compared. The test results are shown in Table 2, from which we can see that the permanent compression ratio and the equivalent storage time of sealing ring are positive correlated. Permanent compression ratio without lateral constraint of sealing ring is 5%–10% higher than the sealing ring with lateral constraint, and it is 20%–25% higher than the standard specimen. Test photos are shown in Fig. 2.

Aging property model of sealing ring can be corrected according to the results of comparative tests mentioned above.

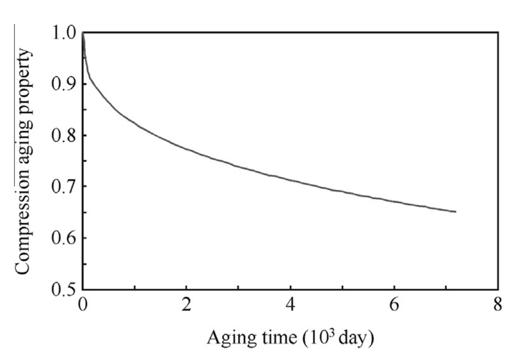
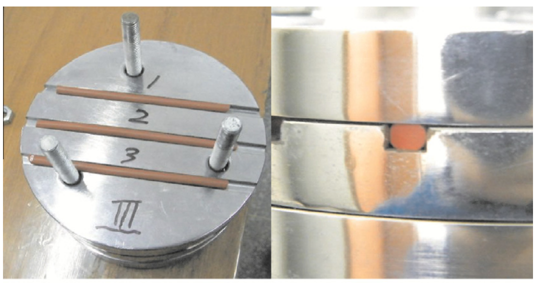


Fig. 1 Compression aging property curve of silicon rubber at room temperature.

Table 2 Permanent compression ratio of sealing ring under different constraint conditions.

Aging time (Year)	Permanent compression ratio		
	Sealing ring		Standard specimen
	Without lateral constraint	With lateral constraint	
10	0.45	0.40	0.28
15	0.54	0.45	0.32
20	0.61	0.56	0.35



(a) Free state of specimen (b) Assembly state of specimen

Fig. 2 Aging property experiments of sealing ring.

In consideration of its compression state during storage, the result of experiment without lateral constraint is adopted. Model parameter K and α are respectively equal to 0.0044 and 0.6, and aging property model after correction is shown in Eq. (5). This model reveals the permanent compression law of sealing rings during longtime storage. The theoretical curve of permanent compression ratio can be derived as shown in Fig. 3, from which we can see that the permanent compression ratio of sealing ring after 20 years of storage is about 60%.

$$f(P) = \exp(-0.0044t^{0.6}) \tag{5}$$

3. Theoretical analysis

3.1. Aging stress analysis

Sealing ring in storage is always in permanent compression state, which will reduce its sealing performance. It is significative to carry out stress analysis in permanent compression, thus to know how the stress state varies with time. Theoretical model of stress aging and relation between stress state and aging state will be built to lay the foundation for storage life evaluation. Three working conditions of sealing ring experiencing during solid rocket motor storage and operation, such as assembly, storage under low pressure, and operation under high pressure have been considered, and sealing ring with 45% permanent compression ratio corresponding to 10 years storage has been taken as an sample.

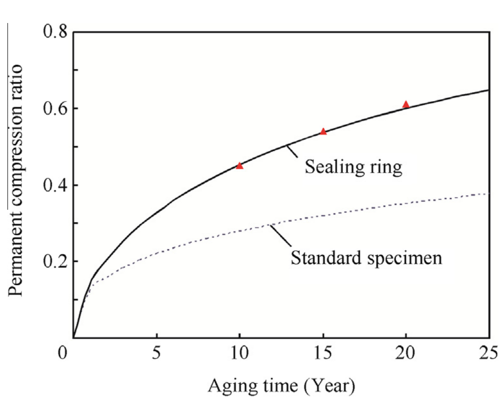


Fig. 3 Theoretical curve of permanent compression ratio.

Mooney–Rivlin model is taken as the hyper elastic constitutive model to simulate rubber materials in computation and the model parameters is obtained by data fitting from uniaxial tensile experiment.[18–21] The main mechanical property of silicon rubber ring which is also obtained by experiment is shown in Table 3. Strain energy density function and the relation between stress and strain in uniaxial tensile are set as shown in Eqs. (6) and (7). In Eq. (6), W is material strain energy density function, I_1 and I_2 are deformation tensor invariant. In Eq. (7), T_i (i = 1,2) represents tensile stress, and λ_i (i = 1,2) represents tensile strain. Subscript "1" means the direction of compression, "2" means its vertical direction.

$$W = 0.82(I_1 - 3) - 0.6(I_2 - 3) \tag{6}$$

$$T_i = 0.82\left(2\lambda_i - \frac{2}{\lambda_i^2}\right) - 0.6\left(2 - \frac{2}{\lambda_i^3}\right) \quad (i = 1, 2) \tag{7}$$

In finite element analysis, element PLANE182 with hyperelastic attribute is adopted for the sealing ring. The edge of the sealing ring contacting the sealing groove is meshed by element CONTA171, while the rigid contacting edge of the sealing groove is meshed by TARGE169. Boundary constraint in different operation conditions is also defined in the following analysis.

Deformation contours and stress contours of sealing ring in assembly are shown in Fig. 4. From which we can see that the contact stress increases initially and then decreases afterwards from the middle to both sides. The maximum point of contact stress is located on the edge of deformation, which numerical value is 0.45 MPa. The shear stress and equivalent stress demonstrate approximately anti-symmetric and symmetric distribution, and the maximum values of them are 0.07 MPa and 0.49 MPa. The maximum of equivalent stress is located in the geometric center.

Deformation contours and stress contours of sealing ring in storage under low pressure with permanent deformation are shown in Fig. 5, from which we can see that there is tiny difference between the stress states in assembly and storage. The contact stress also increases initially and then decreases afterwards from the middle to both sides, but it is relatively larger along the inside edge of permanent deformation. The maximum contact stress is 0.50 MPa. The shear stress and equivalent stress in storage increase little and decrease little in comparison to those of the case of in assembly. The maximum shear stress is 0.10 MPa and the maximum equivalent stress is 0.44 MPa.

Table 3 Mechanical property of silicone rubber ring.

Parameter	Performances	Remarks
Tensile strength (MPa)	7.0	
Elongation rate (%)	300	
Hardness number (HA)	50	Shore hardness
Elastic modulus (MPa)	2	
Poisson ratio	0.499	

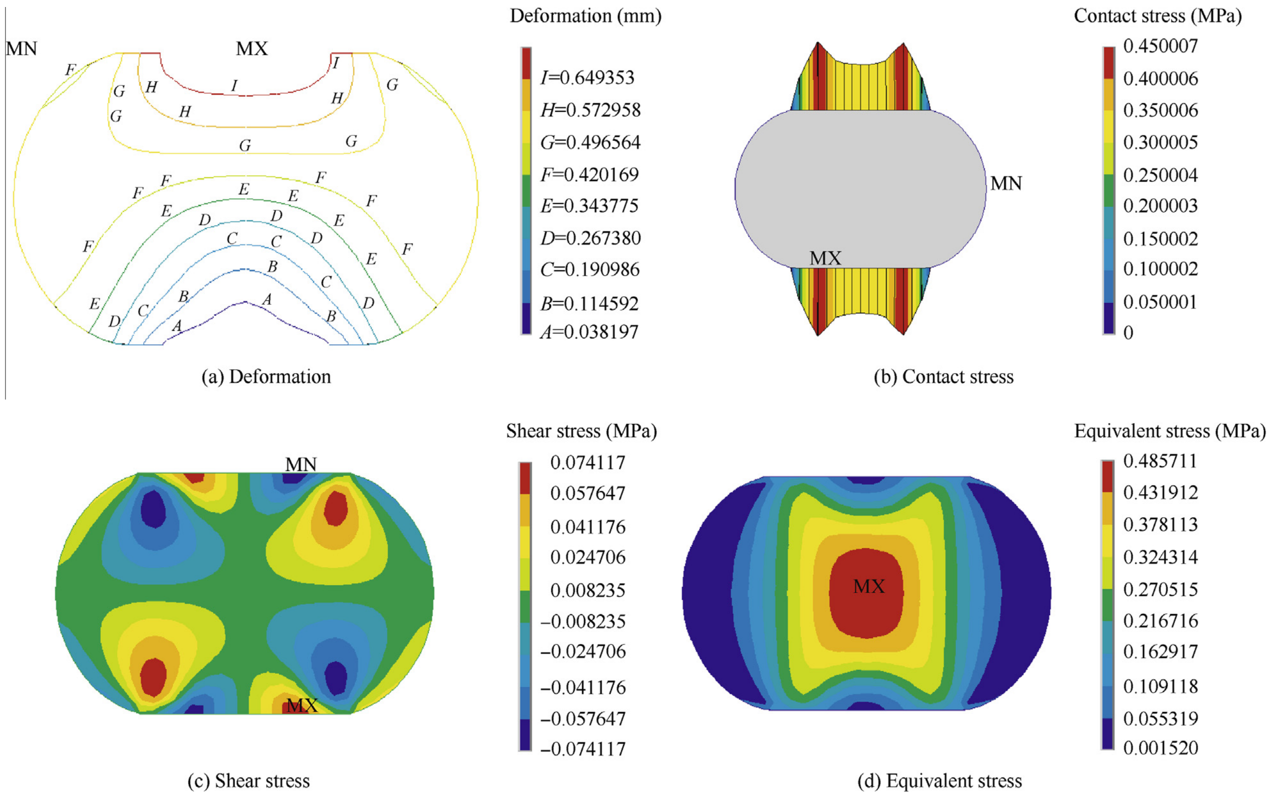


Fig. 4 Stress contours of sealing ring in assembly.

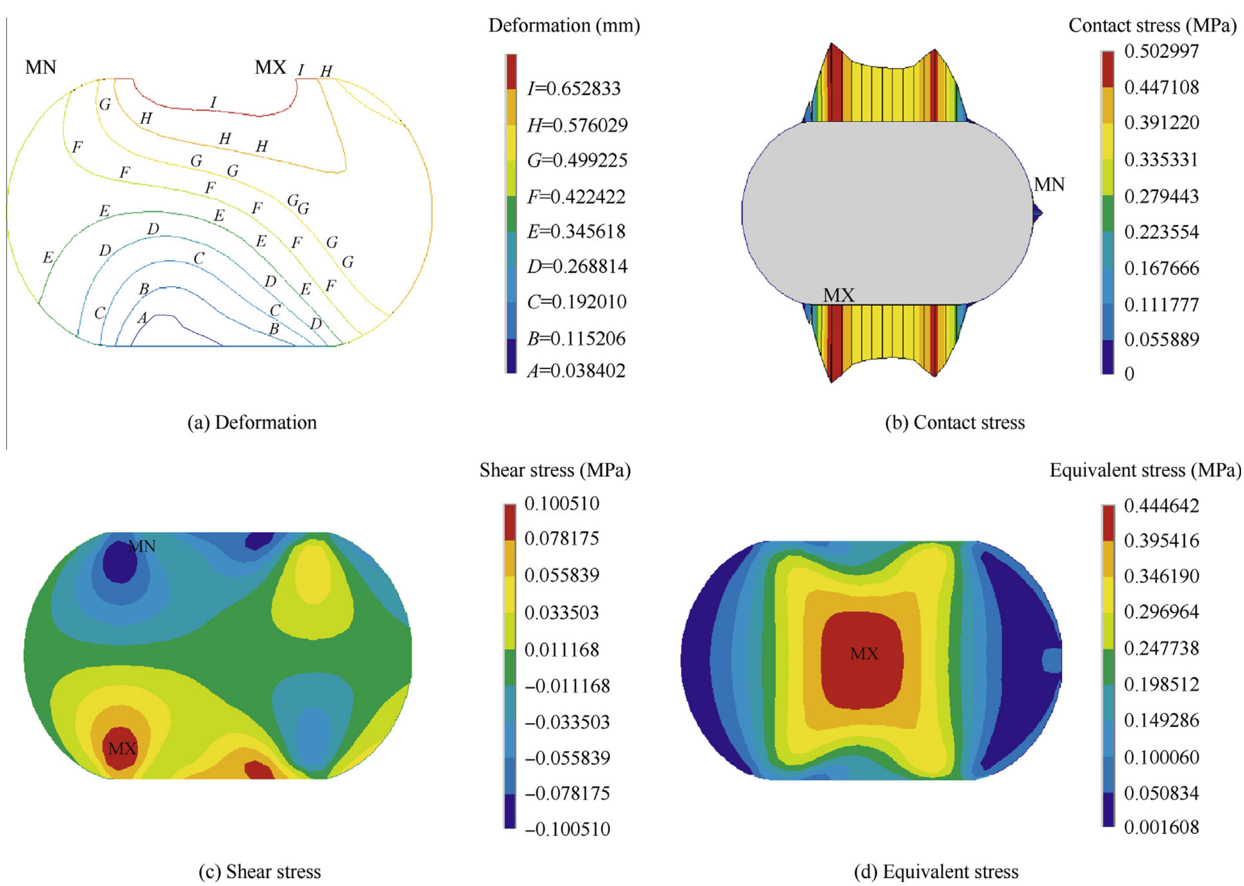


Fig. 5 Deformation contours and stress contours in storage.

Deformation contours and stress contours of sealing ring under operation condition under high pressure are shown in Fig. 6. Contact stress distributes homogeneously on each contact surface. The maximum contact stress on the upper and lower surfaces is 10.79 MPa, and on the outer surface is 10.18 MPa. Shear stress and equivalent stress rise greatly under working condition, and the maximum point of which is located at point angle on the outer surface. The maximum values of shear stress and equivalent stress are 0.34 MPa and 2.36 MPa.

3.2. Relations between aging state and stress state

According to the research results of aging property, this paper chooses different permanent compression ratios corresponding to different aging states to calculate the stress of the sealing ring. The calculation results of the maximum contact stress under different working conditions are shown in Table 4, from which we can see that the contact stress decreases linearly with the permanent compression ratio. The relationship between contact stress and permanent compression ratio can be fitted in equations, in which σ_{N1}, σ_{N2} and σ_{N3} represent contact stress in assembly, storage and operation. γ is the permanent compression ratio.

$$\sigma_{N1} = -0.49\gamma + 0.65 \tag{8}$$

$$\sigma_{N2} = -0.49\gamma + 0.70 \tag{9}$$

$$\sigma_{N3} = -0.46\gamma + 10.83 \tag{10}$$

Table 4 Contact stress under different permanent compression ratio conditions.

Permanent compression ratio	Contact stress (MPa)		
	Assembly	Storage	Operation
0.05	0.60	0.65	10.73
0.10	0.60	0.65	10.59
0.15	0.57	0.62	10.63
0.20	0.57	0.62	10.88
0.25	0.52	0.57	10.60
0.30	0.52	0.57	10.85
0.35	0.51	0.56	10.80
0.40	0.45	0.51	10.55
0.45	0.45	0.50	10.79
0.50	0.44	0.49	10.89
0.55	0.39	0.45	10.49
0.60	0.35	0.39	10.77
0.65	0.34	0.38	10.44
0.70	0.29	0.34	10.33
0.75	0.23	0.29	10.33

The maximum shear stress of sealing ring in assembly, storage and operation is shown in Table 5. The relationship between shear stress and permanent compression ratio is fitted in Eqs. (11)–(13), in which σ_{xy1}, σ_{xy2} and σ_{xy3} represent shear stress in assembly, storage and operation.

$$\sigma_{xy1} = -0.09\gamma + 0.12 \tag{11}$$

$$\sigma_{xy2} = -0.09\gamma + 0.14 \tag{12}$$

$$\sigma_{xy3} = 0.07\gamma + 0.31 \tag{13}$$

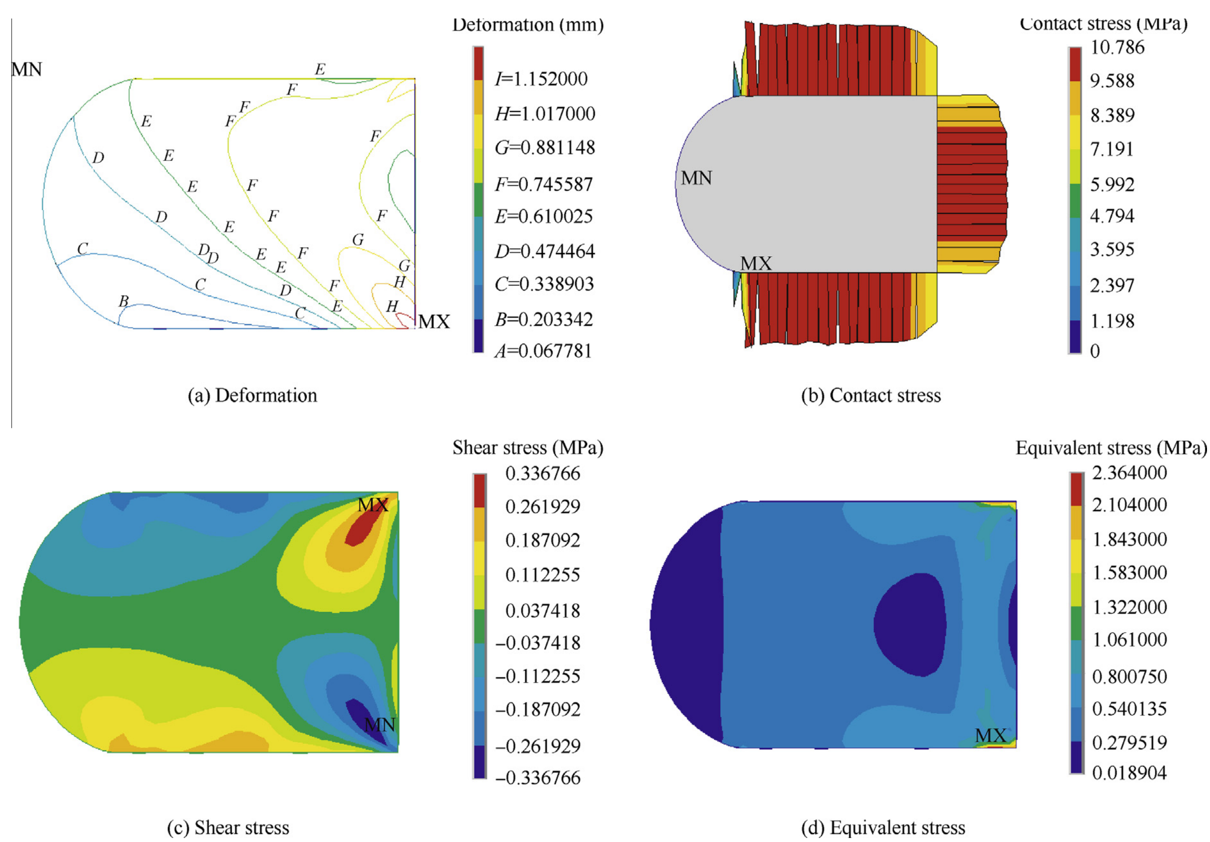


Fig. 6 Deformation contours and stress contours in operation condition.

The maximum equivalent stress of sealing ring in assembly, storage and operation is shown in Table 6. The relationship between equivalent stress and permanent compression ratio is fitted in Eqs. (14)–(16), in which σ_{e1}, σ_{e2} and σ_{e3} are on behalf of equivalent stress in assembly, storage and operation.

$$\sigma_{e1} = -1.06\gamma + 0.97 \tag{14}$$

$$\sigma_{e2} = -1.05\gamma + 0.94 \tag{15}$$

$$\sigma_{e3} = -2.42\gamma + 3.53 \tag{16}$$

The sealing ring with permanent compression deformation can be equivalent to the decline in its amount of compression. Taking contact stress in operation as the research object, 25% compression ratio with different permanent compression ratios can be amended for different amounts of compression and its equivalent relation can be summarized as

$$\hat{\varepsilon} = -0.25\gamma + 0.25 \tag{17}$$

where $\hat{\varepsilon}$ is the equivalent amount of compression.

Table 5 Shear stress in different permanent compression ratio conditions.

Permanent compression ratio	Shear stress (MPa)		
	Assembly	Storage	Operation
0.05	0.11	0.14	0.31
0.10	0.11	0.13	0.32
0.15	0.10	0.13	0.32
0.20	0.10	0.12	0.32
0.25	0.09	0.12	0.33
0.30	0.09	0.11	0.33
0.35	0.08	0.11	0.33
0.40	0.07	0.10	0.34
0.45	0.07	0.10	0.34
0.50	0.08	0.10	0.34
0.55	0.07	0.09	0.35
0.60	0.07	0.09	0.35
0.65	0.06	0.09	0.35
0.70	0.05	0.08	0.36
0.75	0.04	0.07	0.36

Table 6 Equivalent stress under different permanent compression ratio conditions.

Permanent compression ratio	Equivalent stress (MPa)		
	Assembly	Storage	Operation
0.05	0.92	0.90	3.39
0.10	0.88	0.85	3.44
0.15	0.82	0.80	3.28
0.20	0.77	0.74	3.06
0.25	0.71	0.68	2.95
0.30	0.65	0.62	2.86
0.35	0.60	0.56	2.70
0.40	0.54	0.50	2.56
0.45	0.49	0.44	2.36
0.50	0.43	0.39	2.30
0.55	0.38	0.34	2.20
0.60	0.33	0.29	2.06
0.65	0.28	0.25	1.94
0.70	0.23	0.23	1.81
0.75	0.19	0.20	1.75

3.3. Stress aging law

According to the research on aging property model of the sealing ring and relation between stress state and aging state, we can obtain the change law of stress state varying with the storage time. Substituting Eq. (5) into Eqs. (9) and (10), aging model of contact stress in storage and operation can be obtained, just as shown in Eqs. (18) and (19), and the aging curves of contact stress are shown in Fig. 7.

$$\sigma_{N2} = -0.49\left[1 - \exp\left(-0.0044t^{0.6}\right)\right] + 0.70 \tag{18}$$

$$\sigma_{N3} = -0.46\left[1 - \exp\left(-0.0044t^{0.6}\right)\right] + 10.83 \tag{19}$$

4. Storage life evaluation

4.1. Evaluation criterion

Neither dimensional deviation of the sealing ring and the sealing structure nor the fitting clearance and the structure deformation in operation have been considered in aging stress analysis, while such influencing factors should be taken into account in storage evaluation. According to the experience in engineering application, the dimensional deviation of the sealing ring and sealing structure will cause about 4.5% and 3% deviation in compression, and the fitting clearance and the structure deformation will cause 1% and 3% deviation. It means that if deviations mentioned above are assumed to be simultaneous, the effective compression of the sealing ring will decrease by 12.5%. The conclusion that the sealing ring in aging state will lose efficacy if the equivalent compression is less than 12.5% can be obtained. The criterion that the sealing ring maintains its function after aging is shown in Eq. (20).

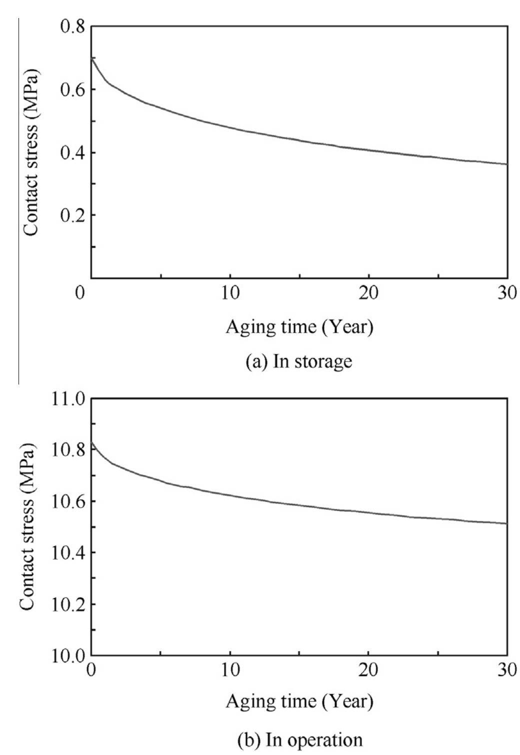


Fig. 7 Aging curves of contact stress in storage and operation.

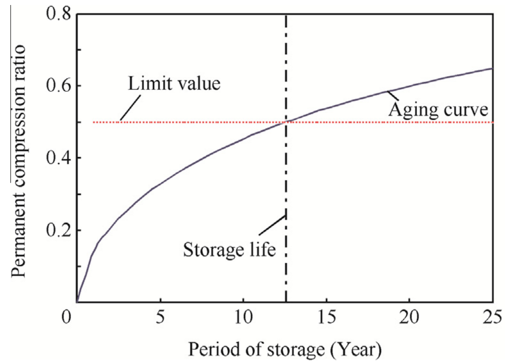


Fig. 8 Diagram for evaluation.

$$\hat{\varepsilon} \gtrsim [\varepsilon] = \Delta\varepsilon = 12.5\% \tag{20}$$

where $\hat{\varepsilon}$ represents the equivalent compression, and $[\varepsilon]$ and $\Delta\varepsilon$ are the tolerance use of sealing rings.

On the basis of the evaluation criterion of the sealing ring and the relationship between the stress state and the aging state of the sealing ring, the limit of the permanent compression ratio can be determined. Therefore, the storage life of the sealing ring can be deduced according to the aging law. In this paper we evaluate that its storage life is 12.6 years, and the diagram for this evaluation is shown in Fig. 8.

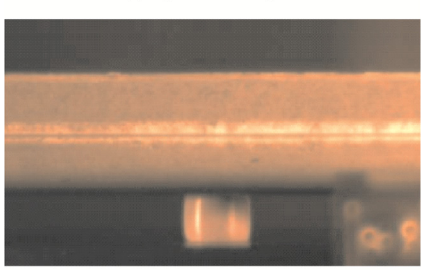
4.2. Verification tests

To verify the evaluation, hydraulic test and rebound rate test have been carried out. The experimental sample is used to simulate the design conditions and artificial accelerated aging in equivalent storage node 10 years and 15 years is conducted. The sealing ring after aging 15 years has been applied in the hydraulic test, but permanent deformation has also produced. Burrs occur in vertex position, which also coincides with the result of stress analysis.

Rebound rate test is carried out to verify whether the rebound of the sealing ring will keep up with the structure deformation at the moment of ignition. A self-made compression release device is designed and a high-speed camera is applied to real-time monitoring. This experiment proves that the average rebound rate of the sealing ring after 15 years aging is 0.18 m/s, which is greater than the spreading rate of the sealing structure. The spreading rate of the sealing structure is less than 0.10 m/s at the moment of ignition. In addition, rebound rate test at low temperature is also carried out to counter the elastic resilience of the sealing ring which has attracted a great deal of attention. The specimen is maintained at the temperature of −40 °C for 24 h, and no subcritical hardening is found. The sealing ring at low temperature still keeps favorable elasticity. Test photos are shown in Fig. 9.

To a certain extent, the experiments carried out above prove the evaluation of the storage life of the sealing ring, which may be able to come to the conclusion that the aging property research and the aging stress analysis are reasonable.

(a) Hydraulic test photo



(b) Rebound rate test photo

Fig. 9 Verification test photos.

5. Conclusions

(1) The storage property aging law and the stress aging law of the sealing ring have been achieved. The storage life of the sealing ring is evaluated and verified by a series of experiments. Research methods and results in this paper can provide reference to the design and life evaluation of sealing structures.

(2) Correlation between aging state and stress state is built, and evaluation criterion of the sealing ring is also established to evaluate its storage life. The evaluation criterion of the sealing ring studied in this paper is the equivalent compression ratio is 12.5%, and the limit of the permanent compression ratio is 50%. Its storage life is evaluated as 12.6 years, which is verified by hydraulic test and rebound rate test.

(3) The research method proposed in this paper can be expanded to other kinds of sealing structures and materials. In the same way, permanent compression deformation is taken as the main aging characteristics in the aging stress analysis; other influencing factors, such as mechanical properties of materials, surface microstructure and thermal conditions have not been included in the research. More aging characteristics and thermal-stress analysis are suggested for further research.

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